



Methods

A critical review of multi-criteria decision making methods with special reference to forest management and planning

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ABSTRACT

This paper provides a review of research contributions on forest management and planning using multi-criteria decision making (MCDM) based on an exhaustive literature survey. The review primarily focuses on the application aspects highlighting theoretical underpinnings and controversies. It also examines the nature of the problems addressed and incorporation of risk into forest management and planning decision making. The MCDM techniques covered in this review belong to several schools of thought. For each technique, a variety of empirical applications including recent studies has been reviewed. More than 60 individual studies were reviewed and classified by the method used, country of origin, number and type of criteria and options evaluated. The review serves as a guide to those interested in how to use a particular MCDM approach. Based on the review, some recent trends and future research directions are also highlighted.

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1. Introduction

Forest resource use decisions are complex because of competing uses such as timber harvesting, recreation, water supply, biodiversity conservation and presence of heterogeneous stakeholders (Ananda and Herath, 2003a,b). Forest policy making involves ecological, socioeconomic, and political processes and values, and making difficult tradeoffs among these multiple objectives (Gregory and Keeney, 1994). There have been major conflicts between timber harvesting and conservation of biodiversity in old-growth forests in the Pacific Northwest region of the U.S. and tropical rain forests in the Amazon River Basin. Stakeholder involvement in the planning, management, and policy analysis can help to resolve conflicts, increase public commitment and reduce distrust between governmental agencies and stakeholders (Tanz and Howard, 1991).

As the complexity of decisions increases, it becomes more difficult for decision-makers to identify a management alternative that maximizes all decision criteria. Planning requires a multi-objective approach and analytical methods that examine tradeoffs, consider

multiple political, economic, environmental, and social dimensions, reduce conflicts, in an optimizing framework.

Multi-criteria decision making (MCDM) is an approach for solving forest resource management problems over the last three decades. Quantifying the value of ecosystem services in a non-monetary manner is a key element in MCDM (Martinez-Alier et al., 1999; Carbone et al., 2000; Munda, 2000). MCDM models improve the information basis of strategic planning, communication, and understanding in natural resource management. MCDM can be used in interactive decision making and a decision support system for policy makers. This paper reviews empirical applications of MCDM in forest management, and policy analysis to assist readers in understanding the assumptions, strengths, and limitations of alternative approaches.

The specific objectives of this paper are to

- review selected MCDM models and their empirical applications in forestry,
- examine the potential of MCDM in decision making in forestry, and
- identify the problems in wider use of MCDM techniques in forestry.

Several authors have reviewed MCDM techniques previously. Herath (1982) and Hayashi (2000) reviewed MCDM applications in agricultural resource management. Romero and Rehman (1987)

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reviewed the applications of MCDM in natural resource management. Smith and Theberge (1987) reviewed the basic theory of measurement and its application in assessing multiple criteria. Stewart (1992) made a theoretical review by identifying pitfalls in using various MCDM approaches. Dyer et al. (1992) presented an account of the historical development of MCDM techniques and evaluating criteria used in the modelling of agricultural systems.

More recently, Kangas et al. (2001), Pukkala (2002) and Kangas and Kangas (2005) reviewed MCDM methods in forest management planning. These reviews show that interactive use of the methods greatly improves the efficiency of the planning process and that it is better to use more than just one MCDM method or a hybrid approach. The review also indicates that there is now a greater interest on MCDM not only of the researcher but also decision-makers and planners outside the scientific community. Sheppard (2005) reviewed MCDM methods in sustainable forest management but this review was limited only to Canadian studies.

The above reviews are weak in terms of empirical information, including comparison of different criteria and weighting methods used and applicability to group decision making problems (Howard, 1991; Smith and Theberge, 1987). All available MCDM reviews, except the review by Hayashi (2000), Pukkala (2002), Kangas and Kangas (2005) and Sheppard (2005) were carried out nearly a decade ago. Only the reviews by Howard (1991), Romero and Rehman (1987), Pukkala (2002), Kangas and Kangas (2005) and Sheppard (2005) examined the MCDM techniques with reference to forestry. Hence there is a gap in the literature on applications of MCDM in forestry in recent years, specifically focusing on empirical challenges and the pros and cons of alternative MCDM techniques.

This review has applications rather than theoretical orientation, and integrates many techniques in a simplified framework. Unlike previous reviews, this review is based on an exhaustive survey of a larger number of journal articles and text books published on MCDM applications in forest management. The review includes both developed and developing countries and covers a longer period, from 1975 to 2008. It focuses on the decision context, problem formulation, and implementation and covers novel features used recently such as the use of visualization techniques for forest landscapes, hybrid methods and new ways to elicit responses under incomplete information which is particularly useful in forestry where full information is often difficult to obtain. The review provides valuable information for policy makers to choose the most appropriate methods for a given forest management problem.

This paper is organized as follows. Section 2 provides a brief introduction to the MCDM approach. The AHP and its variants are discussed in Section 3. In Section 4, the MAUT/MAVT approaches are discussed in detail. Section 5 examines the outranking methods, fuzzy methods and descriptive approaches. Section 6 provides concluding remarks.

2. The MCDM approaches

2.1. Theoretical foundations of MCDM

MCDM is a structured framework for analysing decision problems characterized by complex multiple objectives (Nijkamp et al., 1990; Zeleney, 1984). MCDM can also deal with long-term time horizons, uncertainties, risks and complex value issues. The MCDM process typically defines objectives, chooses the criteria to measure the objectives, specifies alternatives, transforms the criterion scales into commensurable units, assigns weights to the criteria that reflect their relative importance, selects and applies a mathematical algorithm for ranking alternatives, and chooses an alternative (Howard, 1991; Keeney, 1992; Hajkovicz and Prato, 1998; Massam, 1988).

MCDM methods are well suited to deal with forest management and planning problems. There has been a growth in research studies

conducted using MCDM approaches in recent times (Keefe et al., 2004). MCDM has been used in environmental management (Bell, 1975; Bakus et al., 1982; Janssen, 1992), energy policy analysis (Haimes and Hall, 1974; Keeney, 1975; Keeney et al., 1995), farm management (Herath et al., 1982; Xu et al., 1995; Prato et al., 1996), food security (Haettenschwiler, 1994), forest management (Kangas and Kuusipalo, 1993; Kangas, 1994a; Penttinen, 1994; Ananda and Herath, 2003a,b, 2005, 2008), protection of natural areas (Gehlbach, 1975; Sargent and Brande, 1976; Smith and Theberge, 1986, 1987; Anselin et al., 1989), water management (Keeney et al., 1996), ecosystem management (Prato et al., 1996; Prato, 1999a), soil and water management (Prato and Hajkovicz, 2001) and wildlife management (Kangas et al., 1993; Prato et al., 1996), wetland management (Herath, 2004) and national parks management (Prato, 2006).

New techniques and developments of existing techniques, including fuzzy preferences, ways of dealing with interactions among criteria, use of interactive computer software, incorporating visualization have emerged during the last two decades (Fishburn, and Lavalley, 1999; Mendoza and Prabhu, 2005). Empirical MCDM techniques continue to be fine tuned and their application to forestry problems expanded. As applications expand, new insights are gained about how to improve MADM approaches.

2.2. Classification of MCDM techniques

Hajkovicz et al. (2000b) classify MCDM methods under two major groupings namely continuous and discrete methods, based on the nature of the alternatives to be evaluated (Janssen, 1992). Continuous methods aim to identify an optimal quantity, which can vary infinitely in a decision problem. Techniques such as linear programming, goal programming and aspiration-based models are considered continuous. Discrete MCDM methods can be defined as decision support techniques that have a finite number of alternatives, a set of objectives and criteria by which the alternatives are to be judged and a method of ranking alternatives, based on how well they satisfy the objectives and criteria (Hajkovicz et al., 2000a). Discrete methods can be further subdivided into weighting methods and ranking methods (Nijkamp et al., 1990). These categories can be further subdivided into qualitative, quantitative, and mixed methods. Qualitative methods use only ordinal performance measures. Mixed qualitative and quantitative methods apply different decision rules based on the type of data available. Quantitative methods require all data to be expressed in cardinal or ratio measurements (Hajkovicz et al., 2000a).

Value and utility-based approaches use mathematical functions to assist decision-makers to construct their preferences. Multi-attribute value theory (MAVT), multi-attribute utility theory (MAUT), and the Analytic Hierarchy Process (AHP) are the most common approaches within this school. The Analytic Hierarchy Process (AHP), developed by Saaty (1977, 1980), uses the same paradigm as MAVT. However, the AHP uses a different approach to estimate relative values of criteria (weights) and score alternatives over these criteria. The AHP is the source of several other variants, such as the geometric mean approach (Barzilai et al., 1987), REMBRANDT¹ (the multiplicative variant of AHP), and various modifications to incorporate risk and fuzzy concerns.

Many MCDM classifications also distinguish between risk and riskless (certainty) models. MAVT belongs to the quantitative riskless category and MAUT and ELECTRE (Elimination and (Et) Choice Translating Reality) belong to the quantitative risk category. The foundations of decision analysis under risk and uncertainty are provided in expected utility theory (Pollak, 1967; Keeney, 1968;

¹ Basic ideas of the REMBRANDT method are outlined in Lootsma (1993).

Fishburn, 1970; Dyer et al., 1992). In the early periods, most MCDM topics focused on optimization, such as goal programming (Charnes and Cooper, 1961) and vector optimization algorithms (Dyer et al., 1992).

The French school uses outranking techniques such as ELECTRE and PROMETHEE (Preference Ranking Organization Method for Enrichment and Evaluation), which are based on the so-called partial comparability axiom. In contrast to the utility paradigm, Vanderpooten (1990) focused on the idea of learning systems applied to MCDM. The methods that have been developed to support the learning systems approach include VIMDA (Visual Interactive Method for Discrete Alternatives) (Korhonen, 1988) and Aspiration-level Interactive Method (AIM) (Lotfi et al., 1992).

3. Strategic forest planning using Analytic Hierarchy Process (AHP)

The AHP has been widely used for strategic forest planning predominantly in Finland (see Table 1). The theoretical foundations of AHP are presented in Appendix 1. Varis (1989) and Anselin et al. (1989) used AHP in the areas of conservation evaluation and environmental management. Kangas (1992) applied the AHP to an illustrative example of choosing a production plan for a non-industrial forest owner in Finland. The decision hierarchy consisted of overall utility (level 1) as the general goal and four decision attributes (level 2): net income from wood production, yield of other natural products, forest landscape values, and game management. Kangas and Kuusipalo (1993) and Kangas and Pukkala (1996) are examples of operationalising biodiversity using the AHP. In Kangas and Kuusipalo (1993), biodiversity was decomposed into three components: species richness, rarity, and vulnerability of the species. A relative biodiversity index was estimated for each management strategy using a simple linear priority function. The biodiversity index was incorporated into a

forest management/planning problem as a decision criterion along with timber production and game management.

Ananda and Herath (2003b) applied the AHP model to examine forest policy in Australia. Their study shows that AHP can predict stakeholder preferences consistently, though they may not match perfectly. The study indicated that old-growth forest is the most valued attribute. The timber production attribute appeared the second important attribute. The most preferred forest land management option was the option with a high level of conservation and low level of native timber extraction.

Wolfslehner and Vacik (2008) evaluated sustainable forest management (SFM) using the Analytic Network Process (ANP) where indicators of SFM were arranged on a pressure-response (PSR) framework at the forest management unit level. The method supports systematic preference elicitation with pairwise comparisons in a network environment. The ANP was used to evaluate the performance of four management strategies in the North-Eastern limestone Alps in Austria to assess the best sustainable management practices. This approach allows for more detailed information on the network of human influence and their impacts on forest ecosystems.

Except for few studies, the majority of the reviewed studies deal with forest management problems faced by a single decision-maker (see Table 1). However, public forest decision making must account for multiple stakeholders. Kangas (1994a) demonstrated how AHP could be used to explicitly account for the public preferences in forestry using a case study in Ruunaa Nature Conservation Area in Eastern Finland. Duke and Aull-Hyde (2002) is the only application where the general public (in the form of a sample of 129 respondents) were involved in identifying preferences for farmland preservation in Delaware.

Qureshi and Harrison (2001) used AHP to determine how five stakeholder groups ranked four riparian vegetation options for the Johnston River Catchment in North Queensland, Australia. The use of

Table 1
Examples of AHP studies: main features.

Authors (year)	Country	DM ^a	Criteria	Alternatives	Area of evaluation
Ananda and Herath (2003a,b, 2005)	Australia	112	3	3	Forestry
Anselin et al. (1989)	Hypothetical	1	3	–	Ecological evaluation
Mendoza and Sprouse (1989) ^b	USA	1	4	3	Forest planning under fuzzy environments
Varis (1989)	Hypothetical	1	8	6	Reservoir management
Kangas (1992)	Finland	1	3	–	Forest planning
Kangas (1993)	Finland	1	10	10	Evaluating reforestation chain alternatives
Kangas et al. (1993)	Finland	15	5	–	Wildlife habitat index for forest planning
Pukkala and Kangas (1993)	Finland	1	–	4	Heuristic optimization in forest planning
Kangas and Kuusipalo (1993)	Finland	1	9	–	Integrating biodiversity into forest planning
Reynolds and Holsten (1994)	USA	2/3/5	3	–	Risk factors for Spruce beetle outbreaks
Kangas (1994b)	Finland	1	4	6	Incorporating risk attitudes in forestry
Kangas (1994a)	Finland	14	–	–	Public participation in strategic forest planning
Pukkala and Kangas (1996) ^c	Finland	1	4	4	A heuristic method of integrating risk attitudes
Kangas and Pukkala (1996)	Finland	1	–	–	Biological diversity planning using heuristic optimization
Kangas et al. (1996)	Finland	3	5	10	Participatory approach to tactical forest planning
Alho et al. (1996) ^d	Finland	1	5	5	Uncertainty in predictions of the ecological consequences
Alho and Kangas (1997) ^d	Finland	3	3	6	Analysing uncertainties in experts' judgements
Kuusipalo et al. (1997)	Indonesia	1	–	–	Sustainable forest management planning
Leskinen and Kangas (1998) ^d	Finland	–	24	–	Analysing uncertainties in interval judgement data
Mendoza and Prabh (2000)	Indonesia	6	4	10	Evaluation of criteria and indicators for forest sustainability
Kangas et al. (2000a,b) ^e	Finland	1	13	–	Improving the quality of landscape ecological forest planning
Kurttila et al. (2000)	Finland	1	8	5	Forest certification
Proctor (2000)	Australia	22	–	–	Regional forest planning
Quaddus and Siddique (2001)	Bangladesh	1	12	4	Sustainable development planning
Qureshi and Harrison (2001)	Australia	13	4	–	Riparian revegetation options
Duke and Aull-Hyde (2002)	U.S.A	129	12	4	Farmland preservation
Qureshi and Harrison (2003)	Australia	13	17	4	Riparian revegetation options

^a DM = no. of decision-makers.

^b The AHP was used to assess the relative importance of criteria. The study used a fuzzy goal programming model.

^c Optimization was used to find the optimum combination of treatment schedule.

^d The pairwise comparison data were analysed using the regression technique.

^e Bayesian analysis of pairwise comparison data.

prompt cards for pairwise comparisons is one of the innovative features of this study. The study used several MCDM methods to obtain option ranking. Proctor (2000) applied AHP to regional forest planning in Australia. The study focused on the Southern New South Wales forest region. Members of the Southern Regional Forest Forum were taken as the decision-makers for the study. A comprehensive list of criteria, based on the stated objectives of the Regional Forest Agreement, was used to assess the alternative forest plans. Identified criteria were grouped into three broad categories: environment, economic, and social. The results of the study indicated that the two extreme forest use options – the ‘conservation option’ and the ‘timber industry option’ are preferred over the middle ground options.

3.1. Hybrid methods

The potential for integrating MCDM with other analytical methods has been examined by several authors. These hybrid methods provide synergistic accumulation of insights from different methods. Kangas et al. (1993) employed a combination of AHP and regression analysis to incorporate expert judgement in estimating a suitability function for wildlife habitats. Kurttila et al. (2000) presented a new hybrid method that integrates AHP and SWOT (strengths, weaknesses, opportunities and threats) analysis. Kangas (1993) and Pykäläinen and Loikkanen (1997) attempted to integrate AHP and MAUT. Pukkala and Kangas (1993) and Kangas et al. (2001) used heuristic optimization to choose the optimal combination of treatment schedules for forest plans. Objectives were compared in a pairwise manner using a graphical user interface. Other examples of AHP-heuristic optimization in forest planning include Kangas and Pukkala (1996), Pukkala (1998) and Pykäläinen et al. (1999).

Mendoza and Prabhu (2005) used a hybrid approach to estimate a sustainability index using MCDM and integrated this with system dynamics. The study involved management of the communal Mafungautsi Forest in Zimbabwe. The emphasis was on policy action and the study shows that MCDM models can be used in combination with system dynamics models for forest issues.

3.2. Risk preferences

The AHP has been used to examine risk preferences of decision-makers (Crawford and Williams, 1985; Kangas, 1994b; Pukkala and Kangas, 1996; Alho et al., 1996; Alho and Kangas, 1997; Pukkala, 1998). Leskinen and Kangas (1998) presented a technique for deriving the probability distributions for pairwise comparisons and how these distributions can be utilized in the Bayesian analysis of uncertainties of judgements. More applications of Bayesian analysis can be found in Alho and Kangas (1997), Wade (2000), Kangas et al. (2000a,b), Borsuk et al. (2000) and Prato (2001). A stochastic variant of AHP, widely known as the REMBRANDT system,² has also been used to examine the effect of imprecision in the decision-maker's pairwise comparison judgements by expressing each pairwise judgement as a probability distribution. Reynolds and Holsten (1994) examined relative importance of risk factors for Spruce beetle outbreaks using AHP based on a hierarchical model. Application of the AHP is relatively easy and requires less cognitive skills than MAVT and MAUT.

The AHP is generally an easier technique than MAUT to apply because eliciting the required information is less complex. Many decision-makers can respond to the comparisons involved when the number of attributes is small. For this reason, AHP and some of its variants are considered by some as their preferred method (Triantaphyllou, 2001). Selection of attributes should be based upon a thorough examination of the many attributes and that only a few attributes which are very important should be selected. Also innovative methods such as prompt cards can be adopted in multi-person situations and the most appropriate method used to integrate

different stakeholder responses. AHP can be combined with other techniques to get hybrid models so that synergistic insights can be maximized. Risk preferences can also be incorporated with suitable modifications. However, how one constructs the decision hierarchy influences outcomes of AHP. AHP cannot accommodate large number of participants and hence not immune to issues of legitimate representation which appears to hinder its wider application. The roughness of the scale used in the pairwise comparisons and difficulties in keeping the comparison scale constant through the entire evaluation process are problematic issues.

4. Multi-attribute value theory (MAVT) and multi-attribute utility theory (MAUT)

4.1. Multi-attribute value theory

Bell (1975), one of the first applications of MAVT in forestry, used a multi-attribute value function and a utility function to rank alternative management options for a forest pest problem in New Brunswick, Canada (see Appendix 2 for theory)³ Keeney et al. (1990a,b), introduced the ‘public value forum,’ which is based on MAVT to elicit public values for complex policy decisions.

Martin et al. (2000) used the MAVT to evaluate stakeholder preferences for the development of leasable minerals in San Juan National Forest in southwest Colorado in the United States. They developed cardinal value functions for four attributes: watershed improvement, dispersed recreation, species protection, and acres available for leasable mineral development using the mid-value splitting technique. The study stated that the attributes do not need to be independent of each other, but the stakeholder needs to value the attributes independently (Martin et al., 2000).

Martin et al. (2000) highlights several implications of preference modelling. First, the importance of soliciting stakeholder participation at an early stage in the planning process to assist in the development of management alternatives and conflict resolution is recognised. Second, the ability of stakeholders to consistently evaluate a large number of attributes and make tradeoffs among alternatives varies significantly. For instance, preference inconsistencies among stakeholders are common, particularly as the number of alternatives being ranked increases. Hence, the use of both ordinal and cardinal ranking in this study was helpful in uncovering inconsistencies. Although only a few stakeholders took part in the study, the authors pointed out the potential use of the approach in a wider context.

Ananda and Herath (2003a) examined forest policy in north Eastern Victoria and found that MAVT can predict stakeholder preferences consistently. MAVT indicated that old-growth forest is the most valued attribute and timber production, the second important attribute. The most preferred forest land management option was the option with a high level of conservation and low level of native timber extraction. This option differed from the option chosen by the government for North East Victoria. The most preferred forest management option has greater percentage of old-growth forest conserved and a reduced volume of native timber harvest than the current levels implying that the public is willing to conserve more than 60% of old-growth forests. The implied message is that better outcomes with public endorsement can be achieved by using decision analytic techniques. Overall, this technique offers a great potential for any forest planning exercise, increasing the credibility of the process and reconciling conflicting stakeholder values, which is essential for sustainability.

4.1.1. Simple multi-attribute rating technique (SMART)

Stewart and Joubert (1998) proposed a ‘policy scenario’ approach to address the conflicts between conservation goals and land use for exotic

² See Barzillai et al. (1987), Lootsma (1993), Lootsma and Schuijt (1997) for more details.

³ Stillwell et al. (1987) and Keeney et al. (1990a,b) used MAVT to evaluate energy policy options in the U.S.A. and Germany, respectively.

forest plantations in South Africa. In this approach, divergent parties were brought into the decision planning process to evaluate scenario-based policy alternatives in a workshop setting. A simple multi-attribute rating technique (SMART),⁴ which is based on MAVT, was suggested as the method of analysis. The process involves simple scoring of scenarios along a 0–100 scale of relative strength of preferences. Stewart and Scott (1995) used the same approach in a water resources planning problem in South Africa. Other SMART applications include Gardiner and Edwards (1975) on coastal land use planning in California, Joubert et al. (1997) on a water supply problem in South Africa, priority setting in health policy in the Netherlands (Bots and Hulshof, 2000) and allocating research funds in New Zealand (Mabin et al., 2001).

Like SMART, stochastic multi-criteria acceptability analysis (SMAA) is a family of methods developed for discrete multi-criteria problems. SMAA is based on exploring weight-space to describe the valuation that would make each alternative the preferred one. Several applications of SMAA for forest planning have been reported in the literature (Kangas and Kangas, 2004; Leskinen et al., 2004).

4.1.2. Weighted summation

The weighted summation method is one of the most commonly applied MCDM techniques. The theoretical aspects of the method are presented in Appendix 3. Canham (1990) used the weighted summation method to evaluate some hypothetical forest management plans. Qureshi and Harrison (2001) used weighted summation as one of the evaluation methods to compare riparian revegetation options. Hajkowicz et al. (2002) used the weighted summation technique to evaluate eleven management options for Lower Murray Reclaimed Irrigation Areas (LMRIA) in South Australia. Yakowitz and Wertz (1998) addressed the problem of qualitative hierarchical weights and presented an analytical method to calculate the minimum and maximum value scores of the alternatives. The method is applied after commensurate attribute values have been determined for each alternative. It does not require specifying explicit weights for attributes. The decision tool is particularly useful for examining alternatives by multiple decision-makers.

Hill and Assim (1997) proposed a MCDM framework to manage the Macquarie Marshes in Australia. The Nominal Group Technique (NGT) was used in developing the criteria for the study. Group members voted on the importance of the criteria, which allows criteria to be ranked. The authors concluded that the approach is useful in problems where both quantitative and qualitative values are used.

Gregory and Keeney (1994) and Shields et al. (1996) developed frameworks for incorporating stakeholder values in forest planning. The former study focused more on conflict resolution that informs controversial social decisions by structuring stakeholder objectives and using the information to create policy alternatives. Shields et al. (1996) emphasized the use of objective hierarchies to support the goal of incorporating stakeholder preferences into the planning process.

Sheppard (2005) developed an MCDM framework to sustainable forest management (SFM) in Canada which provided specific guidelines for applying and testing participatory MCDM decision support techniques with stakeholder inputs. The framework evaluates alternative forest management plans and shows that the complexity in incorporating sustainability criteria can be adequately handled using MCDM. Sheppard and Meitner (2005) conducted a pilot study at landscape level in the Arrow Forest district in British Columbia. The study involved spatial modelling and landscape visualization, with weightings of sustainability criteria obtained from several different stakeholder groups. This information was combined with expert assessments to derive relative scenario scores in an effects table. Very

few studies have applied visualization techniques in forestry decision support methods. The approach combined expert and stakeholder opinions in a balanced and transparent way – an important consideration for policy makers wary of uncontrolled public input.

4.1.3. MAVT-based valuation

Some forest attributes⁵ such as biodiversity have no market value. Non-market values can be determined using techniques such as contingent valuation (CV) (Mitchell and Carson, 1989). MCDM methods have been modified to value non-marketed environmental resources. Gregory et al. (1993) proposed a constructive approach to value environmental resources. Gregory (2000) implemented the constructive approach by introducing the 'Value Integration Survey' (VIS) method. McDaniels (1996) and Maguire and Servheen (1992) also evaluated policy options using multi-attribute methods. McDaniels and Roessler (1998) used the constructive approach to evaluate wilderness preservation benefits in British Columbia, Canada. A distinct feature of the approach was that selection of attributes and determination of their weights were carried out in a group setting. An innovative feature of this study was that wilderness preservation values were obtained in terms of current and future generations. They concluded that the results are generally comparable to those of a referendum-based (CV) survey. Russell et al. (2001) examined the scope of the multi-attribute utility methods in multi-dimensional valuation problems in forest ecosystems. They followed the original ideas presented in Gregory et al. (1993) and compared a survey based on multi-attribute valuation with a conventional CV survey but were unclear whether multi-attribute techniques improve the quality of environmental valuation.

4.2. MAUT and risk attitudes for forest attributes

The theoretical aspects of MAUT are discussed in Appendix 4. Since MAUT allows complete compensation among all the attributes, it is defined as a complete compensatory model. Multi-attribute utility functions incorporate preferences and uncertainties over all attributes explicitly. Moreover, the tradeoffs among the different attributes are made explicit by the derivation of the scaling constants. Hence, this method has an advantage over lexicography where no tradeoffs between attributes are allowed.

Efforts to apply the utility theory to multi-attribute situations have resulted in the development of procedures for decomposing multi-attribute utility functions. Hyberg (1987) applied multi-attribute utility theory to develop a forest management plan for non-industrial private forest owners in the Sandhill region of North Carolina in the United States. Tradeoffs between timber income and aesthetic quality in shelterwood, seedtree, and clearcut management systems were examined in the study. Timber volumes, value of timber removed in each type of harvest (ranging from clearcutting planting to no stand management), and the corresponding net present values were estimated using volume projection models. Utility functions constructed using a lottery and scalar constants were used to evaluate the options available to the landowners and to determine the management plan that maximizes utility. The landowner's preferences for aesthetic quality were evaluated using lotteries and a series of photographs of various forest stands.

McDaniels (1996) used MAUT to evaluate the environmental impacts of a major Canadian electric utility, BC Hydro.⁶ The approach involved the explicit use of subjective probability to represent uncertainties about impacts when comparing alternatives. First, the best and worst possible levels of each objective were specified. Then the

⁴ See Gardiner and Edwards (1975) and Edwards and Barron (1994) for methodological discussions on SMART.

⁵ The terms 'attributes' and 'criteria' are used interchangeably.

⁶ This study is included here because of its strong links to forestry and methodological relevance.

relative attractiveness of different kinds and levels of environmental impact were established along with the scale for each objective using numerical ratings. An additive utility function then integrated judgements across the various objectives into one overall index. Kim et al. (1998) used an approach similar to the one used by McDaniels (1996) to construct a multi-attribute environmental index for Korea.

Furstnau et al. (2006) examined the overall utility of forest management alternatives with regard to multi-purpose and multi-user settings. The additive utility model was used for six forest management strategies for simulation. The study found that, from an ecological perspective, a conservation strategy would be preferable under all climate scenarios. However, a forest manager in a public owned forest would prefer a strategy with a high share of pine stands.

Edwards and von Winterfeldt (1987) provided three illustrative applications of public values in risk debates. The risk factors were incorporated into value trees (hierarchies) in the three case studies. They used simple weighted summation to clarify risk preferences of the stakeholders. Arriaza et al. (2002) presented a method of constructing utility functions without direct interaction with the decision-makers. The method was applied to simulate farmers' response to changes in the price of water in Spain. Prato (1999b) used an expected utility model with risk neutral preferences to rank five farming systems for an agricultural watershed in Missouri in the United States (see Table 2).

The study of the Regional Forest Agreement in Australia by Ananda and Herath (2005) using MAUT provided useful insights. It showed that stakeholder can have different risk characteristics for the different forest attributes. MAUT predicted the forest policy decisions well and were in line with predictions made using AHP and MAVT. Old-growth forest is the most valued attribute and timber production appeared the second important attribute. The most preferred forest land management option was the option with a high level of conservation and low level of native timber extraction which was not the policy chosen by the Government which was also found by Proctor (2000). The study highlights that one source of forest management conflict in Australia is the absence of adequate participation by stakeholders in making policy decisions. The North East Victoria (NEV) region did not develop formal forest management options with public scrutiny and participation. The conservation of 60% of old-growth forests and the maximum allowable hardwood volume to cut were set by legislation but these levels were not agreed to by stakeholders based on MAUT. MAUT offered increasing credibility to the policy process and reconciling conflicting stakeholder values, which is essential for sustainability.

Kangas et al. (2005) applied stochastic multi-criteria acceptability analysis to examine alternative landscape level plans in Kainuu region, Eastern Finland. The method combines sociological and ecological objectives. MCDM was used to enable holistic comparison of decision alternatives. The sociological landscape planning approach was found to be practicable and the Finnish Forest and Park Service is now applying this model in strategic natural resource management. In Kangas (1993), utility from timber production was measured using a production function while utilities from other uses were measured by incorporating preference functions on a ratio scale. However, these studies did not incorporate risk and uncertainty explicitly.

4.2.1. Probability distributions

The standard version of the MAUT requires specifying consequences of options and subjective probability distributions for uncertain consequences to obtain expected utility scores for each option. Multi-attribute studies involve more than one variable and hence joint subjective probability distributions are needed. If the attributes are stochastically dependent, the elicitation process becomes harder. The stochastic dependence can be verified by comparing marginal probability distributions of the attributes and independent assessment of joint probabilities. If the assessments do not differ or differ only slightly, then independence can be assumed. Alternatively, the independence of marginal and conditional probability distributions of the attributes can be examined.

There are several ways to elicit joint subjective probability distributions. A bi-variate normal distribution has been used to approximate the joint distributions of two variables in the literature (O'Mara, 1971; Lin, 1973; Herath, 1982). For instance, in the case of two attributes, bi-variate joint probability distributions are needed. Although difficult, some studies have managed to elicit joint subjective probability distributions (Herath, 1982). When more than two variables are involved, eliciting multi-dimensional joint subjective probability distributions becomes an impossible task. Delforce and Hardaker (1985) highlighted the difficulties in eliciting subjective probabilities for consequences. For example, respondents may vary their preferences because they have different perceptions of the risks for each attribute level. If subjective probabilities were elicited, then the analysis of the reasons for differences in perceived risk or an explicit analysis of risk can be undertaken.

Several studies have used MAUT to evaluate decisions without using probability distributions. For instance, Raju and Pillai (1999) evaluated the performance of five irrigation canal distributories using MAUT. The estimated single-attribute utility functions were combined using a multiplicative form to derive utility scores for each option without probability information. Kim et al. (1998) did a similar study in which they assessed priorities and value tradeoffs for nine attributes using utility functions. Although their study did not evaluate policy options explicitly, it suggested the use of a multi-attribute index for evaluating environmental policy options.

Delforce and Hardaker (1985) presented another approach to apply MAUT that does not use probability distributions. They assessed a multi-attribute utility function over the descriptive and discrete decision alternatives rather than over the risky consequences of the attributes as in the standard approach to choose from among various land use policies for South Australia's Flinders Range where tourism and pastoralists' interests are in conflict. Five policy variables, namely the extent of tourist access to pastoral tracks, extent of tourist camping access on pastoral lands, extent of tourist off-road vehicle access to pastoral lands, degree of restrictions on grazing practices, and degree of provision of facilities to service pastoralists and tourists were compared. The three descriptive, discrete attribute levels were formulated as actual decision choices faced by the government. These discrete attribute levels were treated as decision options for purposes of utility elicitation and thus the single-attribute utility functions obtained were not continuous.

Probability distributions describe the risk of a decision but when such distributions are not available the situation degenerates into uncertainty. In certain forest management decisions there may be a high degree of uncertainty and decision making is even more difficult in such situations. Many forest management studies do not deal with uncertainty. Kangas and Kangas (2004) provide an overview of different sources of uncertainty and describe how different methodologies can be used to deal with uncertainty in decision making in forest related problems. Examples of selected MAVT/MAUT applications are given in Table 2.

4.2.2. Weighting techniques for utility/value functions

Table 3 presents some of the weighting techniques used in MAVT/MAUT studies. Indifference and swing weighting are the most common weighting methods for multi-attribute value and utility-based studies. Apart from the above methods, point allocation, ordinal ranking, and rating are also used in applications other than forestry.⁷ Estimation of weights can be time consuming and sometimes boring to the respondents (Hayashi, 2000). It is noted that weights that do not incorporate value ranges into the assessment procedure might bias the weights. Swing weighting is considered as one of the most appropriate methods for weight estimation.

The MAVT and MAUT yield more comprehensive information than the AHP but these methods are comparatively more difficult to use.

⁷ See Shoemaker and Waid (1982), Beinat (1997), Hajkowicz et al. (2000b) and Pöyhönen and Hämäläinen (2001) for comparisons of weighting techniques.

Table 2
Examples of MAVT/MAUT studies: main features.

Authors (year)	Country	Method ^a	DM ^b	No. and type of criteria ^c	Criteria	Alternatives ^d
Bell (1975)	Canada	MAUT	E (1)	3/non-linear	Profit; unemployment; recreational value.	–
Delforce and Hardaker (1985)	Australia	MAUT	GP (3)	5/discrete	Access to pastoral tracks; camping access; Off-road vehicle access; Restrictions on grazing; Provision of facilities.	3 (land use options)
Teeter and Dyer (1986)	USA	MAUT	E (22)	2/non-linear	Fire risk; economic efficiency.	7 (fire management strategies)
Stillwell et al. (1987)	USA	MAVT	O (37)	3–13/linear	Health and safety; political/social; financial.	3 (energy policy options)
Hyberg (1987)	USA	MAUT	FO (2)	2/linear	Timber income; aesthetic benefits.	3 (forest management systems)
Keeney et al. (1990a,b)	Germany	MAUT	O (23)	8/discrete	Financial; security; economic; environmental; health; social; political; international impacts. flora; fauna; wilderness ecosystems.	6 (energy policy options)
McDaniels (1996)	Canada	MAUT	E (1)	6/linear	Recreation; aesthetics; global impacts.	3 (hydro-electric project sites)
McDaniels and Roessler (1998)	Canada	MA/CV	O (28)	3	Ecological values; human demand values; human spiritual values.	2 (wilderness policy options)
Kim et al. (1998)	Korea	MAUT	E (1)	9/non-linear 9	Environmental impacts (6); health effects (2); global warming (1)	3 (power development plans)
Stewart and Joubert (1998)	South Africa	MAVT	GP	–	Employment; housing; well-being; agriculture; forestry; tourism; industry; conservation; water.	6 (land use scenarios)
Prato (1999b)	USA	MAUT	O (20)	5(linear)	Net return; risk; water quality; ecosystem; soil erosion.	5 (farming systems)
Raju and Pillai (1999)	India	MAUT	E (3)	8/piecewise-linear	Farm development works; adequacy of water; inputs; conjunctive water use; productivity; participation; economic; social impact.	5 (irrigation systems)
Gregory (2000)	USA	MA/CV	GP (180)	7	Fish habitat; preservation of old-growth forests; cost; fire fighter injuries; timber harvest; forest jobs; forest recreation.	3 (environmental policy options)
Martin et al. (2000)	USA	MAVT	GP (3)	4/non-linear	Leasable development; watershed improvement; dispersed recreation; species protection.	6 (land use options)
Russell et al. (2001)	USA	MA/CV	GP (131)	6	Tree size; forest type; visible plant damage. Patchiness; recreational intensity; extraction intensity.	3 (blended forest options)
Arriaza et al. (2002)	Spain	MAUT	–O	2	Profit and variance in total gross margin.	–
Hajkowicz et al. (2002)	Australia	WS	(10)	6	Efficiency; employment; wetland; salt load; tourism; health risks.	11 (management options)

^a MAVT = multi-attribute value theory; MAUT = multi-attribute utility theory; MV/CV = multi-attribute contingent valuation; WS = weighted summation.

^b DM = decision-makers; E = experts; GP = general public; FO = forest owners; O = others. The size of the total sample is given in the parenthesis.

^c No. of criteria/type of value (utility) function.

^d No. of alternatives/the content of alternatives is explained in the parenthesis.

The utility elicitation using iterative question protocols is time consuming and complex. In most MAVT and MAUT studies reviewed here, the decision-makers were experts, except in valuation studies where the inputs were provided by the general public.

But it is feasible to use MAVT and MAUT by innovative adaptations such as the use of utility indices. Other modifications such as prompt cards, pictorial presentations with visual impact have been used under MAVT and MAUT. Heuristics can be also be adopted in situations where the goals are not necessarily maximizing but simply satisficing.

Potential exists in developing innovative methods to simplify the elicitation procedures in utility-based methods. What is most desirable is to apply the MAUT-based approaches in actual forestry situations to generate greater interest among policy makers. Whether MAUT and MAVT approaches are predictive of actual behavior has not been widely documented. Despite these difficulties, Martin et al. (2000) holds much promise in future use of MAUT and MAVT.

5. Other MCDM methods

5.1. Aspiration level approaches

Aspiration level approaches use a variety of multi-objective goal programming (GP) techniques (see Appendix 5 for a theoretical presentation of goal programming methods). Limitations in conventional mathematical programming with regard to practical multi-objective decision situations paved the way to develop more realistic planning models, which accommodate the preferences of the decision-maker. The ‘satisficing’ concept of Simon (1983) states that the natural decision making heuristic is to improve what appears to be the most

critical problem area (criterion) initially until it has been improved to some satisfactory level of performance. Attention is then shifted to the next most important criterion and so on. GP formalises this heuristic (Stewart, 1992). The aspiration level approach can be regarded as a generalisation of GP.

The main idea is to construct a mathematical basis for satisficing decision behavior by introducing the wishes of the decision-maker as basic a priori information in the form of aspiration levels (reference points) (Munda, 1995). In general, the decision-maker may find it extremely difficult to find a solution that is as near as possible to the target. This requires a measure of ‘distance’ or discrepancy from the target.

Table 3
Weight elicitation methods of selected MAVT/MAUT studies.

Authors (year)	Method
Bell (1975)	Indifference (variable probability method)
Delforce and Hardaker (1985)	Indifference (variable probability method)
Teeter and Dyer (1986)	Indifference (ELCE method) ^a
Hyberg (1987)	Indifference (ELCE method)
Keeney et al. (1990a,b)	Swing weighting
McDaniels (1996)	Direct rating
McDaniels and Roessler (1998)	Direct rating
Stewart and Joubert (1998)	Direct rating
Raju and Pillai (1999)	Indifference
Gregory (2000)	Swing weighting
Martin et al. (2000)	Swing weighting
Russell et al. (2001)	Swing rating

^a ELCE = equally likely certainty equivalent method.

Table 4
Examples of optimization and outranking studies: main features.

Author/s (year)	Country	Model ^a	O/C ^b	DV ^c	Area of evaluation
Schuler and Meadows (1975)	USA	GP	4/2	8	National forest planning.
Kahalas and Groves (1978)	USA	GP	6/16		Profit versus social values in forestry.
Mendoza et al. (1987)	Canada	MOP	5/7		Multiple-use forest planning.
Teclé et al. (1994)	USA	MOLP (PARETO RACE)	6/2		Interactive multi-objective forest planning.
Teclé et al. (1995)	USA	MOP	6/2	6	Conflict analysis in multi-resource forest management.
Boxall et al. (1996)	Canada	CM	10		Moose hunting preferences in wildlife management units.
Fischer et al. (1996)	Kenya	ARBDS ^d		3	Land use planning.
Dennis (1998)	USA	CA	–	5	Public preferences on forest attributes.
Pukkala (1998)	Finland	HERO ^e	–	–	Multiple risks in multi-objective forest planning.
Stevens et al. (1999)	USA	CA	6	–	Preferences on co-operative agreements in forestry.
Pykäläinen et al. (1999)	Finland	IDA ^f	4	5	Participatory strategic forest planning.
Wikström and Eriksson (2000)	Sweden	HERO	–	–	Stand management problems under biodiversity considerations.
Church et al. (2000)	USA	Spatial Optimization	–	–	Decision Support for forest ecosystem management.
Varma et al. (2000)	Australia	LP	–	–	Aspiration-based utility functions for sustainable forest mgmt.
Farber and Griner (2000)	USA	CA	–	–	Valuing watershed improvements.
Kangas et al. (2000a,b)	Finland	PROMETHEE/ELECTRE ^g	–	–	Ecological forest planning using advance decision support.
Kurttila et al. (2001)	Finland	MNL	–	–	Attitudes towards the operational environment of forestry.
Hjortso and Stræde (2001)	Lithuania	LP/MOLP	–	–	Strategic multiple-use forest planning.
Prato (2001)	USA	MASTEC/AEM ^h	–	–	Modelling carrying capacity in national parks.

^a GP = goal programming; MOP = multi-objective programming; MOLP = multiple objective linear programming; CM = choice modelling; CA = conjoint analysis; MNL = multi-nomial logit.

^b O = objectives; C = constraints.

^c DV = decision variables.

^d ARBDS = aspiration-reservation based decision support system based on multi-objective optimization coupled with MCDM.

^e HERO = heuristic optimization algorithm.

^f IDA = interactive decision analysis using HIPRE program, based on several multi-criteria weighting techniques.

^g PROMETHEE II and ELECTRE III are outranking methods.

^h MASTEC = multiple attribute scoring test of capacity. This method uses a stochastic multiple attribute programming model. AEM = adaptive ecosystem management model, which uses the Bayes rule.

Archimedean, Preemptive and Tchebycheff or Minimax are three discrepancy measures that have been proposed to measure the discrepancy (Stewart, 1992). Fischer et al. (1996) developed an extension to the aspiration level method in an attempt to develop a decision support system called 'Aspiration-Reservation Based Decision Support' (ARBDS). The ARBDS links the properties of the Pareto-optimal solutions with the aspiration and reservation levels set interactively by the user for each criterion. The method combined with the GIS land resource database can provide a powerful decision support tool.

5.2. Outranking methods

Implicit in value-based approaches are the assumptions that there is always: (1) scope for some form of compensation between attributes (a decrease in performance in one attribute can be compensated by an increase in performance in another attribute); and (2) the existence of a true ordering of alternatives which needs to be discovered (Stewart, 1992). The outranking method allows the above assumptions to be relaxed by invoking the partial comparability axiom.⁸ According to this axiom, preferences can be modeled by means of four binary relations: indifference, strict preference, large preference, and incomparability (Munda, 1995). The most widely used outranking methods are ELECTRE (Roy, 1977) and PROMETHEE (Brans et al., 1986). Appendix 6 provides the theoretical details for selected outranking methods.

Raju and Pillai (1999) carried out a comparative evaluation of MCDM techniques in a case study of Chaliyar river basin planning in Kerala, India. Five MCDM methods, namely ELECTRE-2, PROMETHEE-2, AHP, Compromise Programming⁹ and EXPROM-2 were employed to select the best reservoir configuration for the river basin. They used a Spearman rank correlation coefficient to assess the correlation between the ranks obtained by the above MCDM methods. Although these MCDM methods follow different approaches, analysis has shown that the same preference strategy is reached by all methods. Abu-Taleb and Mareschal (1995)

applied PROMETHEE V to evaluate and select potentially feasible water resources development options in Jordan. The procedure involved identification and mathematical formulation of objectives, constraints, options and construction of an evaluation matrix. The programme provides the best compromise solution. Some examples of optimization and outranking applications are given in Table 4.

5.3. Fuzzy methods

Zadeh's fuzzy set theory provides a rigorous and flexible approach to complex resource management problems (1965). Forest systems are inherently complex and therefore lend themselves naturally to fuzzy approaches in planning and decision making. The fuzzy set approach uses imprecise and uncertain information. This approach specifies each alternative with some degree of membership. A fuzzy set is a class with un-sharp boundaries (i.e., a class where transition from membership to non-membership is gradual rather than abrupt; Gupta et al., 2000). The role played by fuzziness in human cognition encourages formulation of real-world problems using a fuzzy approach. Further, a decision-maker might not be able to express his goals or constraints precisely because his utility function is not defined or cannot be defined accurately (Gupta et al., 2000).

Mendoza and Sprouse (1989) proposed a forest planning approach using fuzzy set theory. Ducey and Larson (1999) showed how a simple tabular technique using fuzzy sets can be used to compare complex management alternatives, incorporate multiple objectives and identify knowledge gaps and areas of disagreement. Gupta et al. (2000) presented a case of incorporating MCDM and simulation models into a multi-objective fuzzy linear programming model. Saaty's AHP can be generalised to include fuzzy information. However, it requires knowing the relative importance of criteria before alternatives can be eliminated (Terano et al., 1994; Ducey and Larson, 1999). NAIDE (Novel Approach to Imprecise Assessment and Decision Environments) (Munda, 1995) is an example of framing fuzzy uncertainty. De Marchi et al. (2000) provide an application of the NAIDE method to examine water resource policy options. Prato (2007a,b) presented a theoretical framework to apply fuzzy logic to evaluate ecosystem sustainability. Kangas et al. (2007) used

⁸ See Arrow and Raynaud (1986) for a description of outranking axioms.

⁹ Compromise programming (CP) uses a distance measure in which the best is at the least distance from the ideal point in the set of efficient solutions.

ecological and social sustainability variables, in forest planning using fuzzy additive weighting. They represented qualitative data in the form of linguistic variables to incorporate uncertainty. The fuzzy additive weighting revealed greater uncertainty than the statistical approach. They recommend use of statistical methods but if probability distributions for the uncertain variables cannot be obtained the fuzzy approach has been found to be useful.

5.4. Descriptive approaches

Most of the methods discussed above are partially normative in the sense that they aim to provide some form of guidance regarding the ranking of alternatives. Descriptive methods examine the relationships between the attributes or variables in statistical terminology, so as to develop an understanding of what can be realistically achieved, and what constraints on performance are imposed by the current decision set are (Stewart, 1992). These models involve inferring the decision-maker's preferences from past choices. Linear statistical models, disjunctive and conjunctive strategies, and lexicography can be used to construct multi-attribute decision models. Linear statistical models can be classified into two designs: those using analysis of variance and those using multiple regression. These methods belong to the inferred preference approach because they infer the decision-maker's preferences from past choices and use those preferences as inputs to a linear statistical model. Factor analysis, correspondence analysis, and principal components analysis can be used to identify tradeoffs among attributes. Some applications include Rivett (1977), Clark and Rivett (1978), Stewart (1981), Mareschal and Brans (1988).

5.5. Conjoint analysis

Conjoint analysis is a multivariate technique widely used in marketing research to measure consumer preferences. The objective of conjoint analysis is to decompose a set of factorially designed attributes (or stimuli) so that the utility of each attribute can be inferred from the respondent's overall evaluations. The partial utilities can be combined to estimate relative preferences for any combination of attribute levels (Hair et al., 1998).

Dennis (1998) presented a conjoint ranking survey designed to solicit public preferences for various levels of timber harvesting, wildlife habitats, hiking trails, snowmobile use, and off-road-vehicle access in the Green Mountain National Forest in the United States. Bennet et al. (2000) presented a framework to analyse value preferences of forestry products and services using choice modelling, a variant of conjoint analysis. Farber and Griner (2000) provided a case study on forestry using conjoint analysis. Kurttila et al. (2001) used the multinomial logit model to examine forest management decisions of private forest owners relevant to strategic management concept. Stevens et al. (1999) used conjoint analysis to elicit landowner attitudes and preferences towards co-operative management agreements involving both timber and non-timber objectives in the Franklin County, Massachusetts in the United States. A potential problem with conjoint analysis is that because the individual responses are made in the context of a hypothetical situation, actual behavior of respondents may be different than estimated behavior.

The above methods provide easy alternatives in situations with unspecified problems. Some of these methods can be used together to test the various alternative managements approaches available. The fuzzy approach is useful where uncertainties are present. These methods can be combined to get hybrid models that have useful results. Sustainable forest management is a goal of many governments and the sustainability concept can be incorporated into fuzzy models. The descriptive approach uses statistical approaches and belongs to the inferred preference approach based on past choices but they permit assessment of the tradeoffs involved among multi-attribute approaches. Some methods are very familiar in marketing research but can be used in multi-attribute forest management situations.

6. Discussion and conclusion

The above review indicates that MCDM is relevant and can contribute to improving forest management decisions. The review identified several trends in the use of MCDM in forestry. Firstly, it shows that theoretical developments have moved faster than empirical applications of MCDM. Empirical applications of MCDM in forest management are less compared to say applications in water resources management. A similar conclusion was drawn in the review of Romero and Rehman (1987) where they have noted some resistance to the acceptance of MCDM as a worthwhile framework for analysing land use problems. Use of MCDM in developing countries is limited due to issues such as lack of expertise, finance and technology.

Early applications appear to be biased towards methods such as the AHP which is relatively easier, flexible and requires less cognitive skills than say, MAUT. There is a trend in using several alternative MCDM models to provide comparative information and enhance the efficacy and empirical validity of results. Recent literature also shows a shift towards using hybrid methods (e.g. AHP has been combined with other models), as highlighted in the review by Kangas and Kangas (2005), so that synergies can be maximized. There appear to be some concentrations in certain countries such as Finland which has reported many MCDM studies. Studies that attempt to integrate MCDM methods with participatory natural resources planning predominantly are featured for Finland. Algorithms, computerized decision aids and innovative advancements in MCDM informatics available can accelerate the use of MCDM in forest management problems. Romero and Rehman (1987) noted an excessive reliance on the use of Goal Programming in forest planning problems. However, it appears that studies based on Goal Programming have diminished over time whilst AHP and other hybrid studies have proliferated.

There is greater acceptance of the importance of uncertainty and several MCDM applications have incorporated uncertainty using fuzzy set models. Potential exists to simplify theoretical perspectives of MCDM with innovative adaptations (e.g. use of utility indices without eliciting probability information).

The greater use of MCDM models in forestry requires modifications to the complex aspects of MCDM to render them less arduous and encourage innovations in use of MCDM. Some MCDM models such as MAVT and MAUT yield more comprehensive information but these methods are comparatively more difficult to use because of additional complexity involved in eliciting stakeholder preferences. Innovative adaptations may be needed to account for presence of unique features in developing country forestry such as the critical role of non-timber products.

Expanding empirical applications need innovations in several other areas. For example, there is need to refine decision criteria to reduce their vagueness, add clarity and limit analysis to a manageable set of attributes, to reduce tediousness is interview procedures and enhance the decision-makers grasp of the choices being made without obscuring important issues and value judgements. The process of criteria selection is another area that needs greater clarity. The utility elicitation question protocols are time consuming and complex and few decision-makers can provide in precise detail information on objectives, goals, targets, weights etc. Elicitation should be made easier and accurate through innovative methods that use schematic diagrams, visualization techniques, prompt cards and pictorial presentations. These innovations should facilitate wider use of MCDM and avoid MCDM degenerating into blind applications of mathematical techniques.

MCDM should bring a greater degree of reality to the policy process by resolving complex forest management issues. But MCDM is not a prescriptive answer but a transparent and informative decision process which helps to uncover how peoples' intuitive decision procedures can be informed by a structured rational analytic process.

Forest management is dynamic and the objectives are evolving towards sustainable management/adaptive management. A significant gain can be made if MCDM models are developed innovatively to

capture the changing dynamics of forest management. MCDM can achieve sustainable use of forest resources through by facilitating collaborative decision making and conflict resolution. Future research should be directed towards developing guidelines and most appropriate MCDM methods. It is through the cumulative efforts that the generality and utility of MCDM will be advanced. The challenge is to foster development of true collaborative practices to support the conviction that state forests ultimately belongs to the community.

Appendix A

Analytic Hierarchy Process (AHP)

The theoretical foundations of AHP were developed by Saaty (1977, 1980). AHP aggregates the separate criteria into an integrated criterion (Bouma et al., 2000). When applying the AHP, the preferences of the decision elements are compared in a pairwise manner with regard to the element preceding them in the hierarchy. If two criteria are of equal importance, a value of 1 is given in the comparison, whereas a value of 9 indicates the absolute importance of one criterion over the other. The difference between two adjacent scores may not be highly distinct, however.

Pairwise comparison data can be analysed using either regression analysis or an eigenvalue technique.¹⁰ In the eigenvalue technique, the reciprocal matrices of pairwise comparisons are constructed. The right eigenvector of the largest eigenvalue of matrix A (Eq. (1)) constitutes the estimation of relative importance of attributes. The pairwise comparisons made by the respondents can be synthesised into pairwise comparison matrices, which take the following form:

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \tag{1}$$

where a_{ij} represents the pairwise comparisons rating for attributes i and j .

Given the reciprocal property, only $n(n-1)/2$ actual pairwise comparisons are needed for an $n \times n$ comparison matrix. Saaty (1977) proposed the right eigenvector method that constructs the vector of priority weights and facilitates testing for inconsistency. In the case of perfect consistency,

$$AW = nW \tag{2}$$

where A is the $n \times n$ comparison matrix and $W = (w_1, w_2, \dots, w_n)^T$. Saaty (1977) proposed the following definition

$$AW = \lambda_{\max} W \tag{3}$$

where λ_{\max} is the maximum eigenvalue (Perron root) of matrix A . Saaty (1977, 1980) proved that the largest eigenvalue λ_{\max} is always greater than or equal to n (number of rows or columns).

Appendix B

Multi-attribute value theory (MAVT)

The MAVT is a useful framework for decision analysis with multiple objectives (von Winterfeldt and Edwards, 1986). The utility function

¹⁰ Crawford and Williams (1985) showed how pairwise comparisons data can be analysed using regression analysis. The evidence suggests that both eigenvalue and regression techniques yield similar results (Alho and Kangas, 1997).

in MAUT applies to outcomes of decision options, which are uncertain (Keeney and Raiffa, 1976). The subjective judgement of the decision-maker to evaluate tradeoffs among alternatives are obtained either implicitly or explicitly by formalising a value structure.

Decomposed scaling and holistic scaling are the most widely used assessment strategies in MAVT (Beinat, 1997). In decomposed scaling, the marginal value functions and weights are assessed separately. Holistic scaling is based on the overall judgements of multi-attribute profiles. Weights and value functions are estimated through optimal fitting techniques such as regression analysis or linear optimization. Decomposed scaling holds a definite edge over holistic scaling with respect to simplicity of estimation and accuracy (Beinat, 1997).

The individual attribute value functions weighted by scaling constants generate an aggregate value function V^i for an individual or stakeholder group. When the value function has three or more criteria the preferential independence assumption is generally used to simplify the assessment. The theorem that follows from the above assumptions is as follows. Given attributes $Y_1, \dots, Y_n, n \geq 3$, an additive value function

$$V(Y_1, \dots, Y_n) = \sum_{i=1}^n \lambda_i V_j(Y_j) \tag{4}$$

where

- (a) V_j (worst Y_j) = 0, V_j (best Y_j) = 1, $j = 1, 2, \dots, n$;
- (b) $0 < \lambda_j < 1, j = 1, 2, \dots, n$;
- (c) $\sum_{j=1}^n \lambda_j = 1$.

$V(Y_1, \dots, Y_n)$ represents the multi-attribute value function of (Y_1, \dots, Y_n) , V_j denotes generic notation for each attribute, $V_j(Y_j)$ represents value functions for each attribute and λ_j represents the weighting factors (Keeney and Raiffa, 1976). It has been shown that the non-additive (i.e. interaction) effects tend to be swamped by the additive effects (Yntema and Torgerson, 1967).

Appendix C

Weighted summation

Weighted summation method requires standardisation of all performance measures into commensurate units. The performance measures are standardised using the following formulae:

$$s_{ij} = \frac{x_{ij} - \min j}{\max j - \min j} \text{ (for criteria where more is better)} \tag{5}$$

$$s_{ij} = \frac{\max j - x_{ij}}{\max j - \min j} \text{ (for criteria where more is worse)} \tag{6}$$

where:

- s_{ij} = the standardised performance measure of the i th alternative against the j th criterion;
- x_{ij} = the performance measure for the i th alternative against the j th criterion;
- $\min j$ = the minimum performance measure for all alternatives against the j th criterion; and
- $\max j$ = the maximum performance measure for all alternatives against the j th criterion.

An overall performance measure is calculated for each alternative by multiplying the standardised score for each attribute by the

corresponding attribute weight and summing across attributes. The formula for determining the overall performance of each alternative is:

$$v_i = \sum_{j=1}^m w_j s_{ij} \tag{7}$$

where:

- v_i = the overall performance of the i^{th} alternative;
- m = the number of criteria;
- w_j = the percentage weight of the j^{th} criterion; and
- s_{ij} = the standardised performance measure of the i^{th} alternative against the j^{th} criterion.

Appendix D

Multi-attribute utility theory

MAUT is based on expected utility theory (Savage, 1954; Fishburn, 1970). Keeney (1971) provided a theoretical framework and a set of assumptions, which decompose the multi-attribute utility function into a more useable form. The concept of utility independence concerns lotteries over only one attribute, though it may be a vector attribute. Consider a multi-attribute utility function of the form of $U(Y_1, Y_2, Y_3)$. The attribute Y_i is utility independent of the other attributes, which might be designated as Y_i^* , if preferences for lotteries over Y_i , with other attributes held at a fixed level, denoted by Y_i^* , do not depend on what those levels are. Put differently, utility independence implies that the decision-maker's attitude towards risk with respect to Y_i is not affected by the amounts of the other fixed attributes.

Keeney and Raiffa (1976) described ways to check for utility independence. The theorem, which follows from utility independence, is as follows. If each Y_i is utility independent of Y_i^* , $i = 1, \dots, n$, then the utility function is either additive

$$U(Y_1, \dots, Y_n) = \sum_{i=1}^n k_i U_i(Y_i) \tag{8}$$

or multiplicative

$$1 + KU(Y_1, \dots, Y_n) = \prod_{i=1}^n [1 + Kk_i U_i(Y_i)] \tag{9}$$

{ where U and U_i are utility functions scaled from zero to one, the k_i s are scaling constants with $0 < k_i < 1$, and $K > -1$ is a non zero scaling constant. If U is multiplicative

$$\sum_{i=1}^n k_i \neq 1,$$

and if additive

$$\sum_{i=1}^n k_i = 1.$$

The additive form is the simplest form that can be assumed. Keeney and Raiffa (1976) provide a complete theoretical proof of different utility functions and related work.

Appendix E

Goal programming

Goal programming (GP) has been used extensively to solve multiple-use forest management problems. GP is a variant of linear programming that formulates the objective function using deviational

variables in the goal constraint equations. The mathematical form of the general goal programming model is as follows:

$$\text{Min } z = \sum_{i=1}^n P_i d_i^- + P_i d_i^+ \tag{10}$$

subject to

$$\sum_{j=1}^n a_{kj} x_j \leq b_k \quad k = 1, \dots, s; \quad i = 1, \dots, n. \tag{11}$$

$$\sum_{j=1}^n \Omega_{ij} x_j + d_i^- - d_i^+ = g_i \tag{12}$$

$$x_j, d_i^-, d_i^+ \geq 0 \tag{13}$$

$$d_i^-, d_i^+ = 0 \tag{14}$$

where x_j = activity variable, P_i = weighting function, d_i^+ = over-achievement of goal (i), d_i^- = under-achievement of goal (i), a_{kj} = input-output coefficient between system constraint (k) and activity (j), b_k = system constraint, Ω_{ij} = input-output coefficient between goal constraint (i) and activity (j) and g_i = goal constraint. Essentially, the GP model attempts to minimise the sum of weighted deviations from specific goals, while adhering to a set of operational constraints.

Appendix F

ELECTRE methods

ELECTRE methods represent the characteristics of the decision-maker's preferences by pairwise concordance and discordance tables calculated for each criterion. The concordance index expresses the fuzzy membership value of the statement as alternative a is at least as good as alternative b in terms of criterion i . The discordance index evaluates the 'comparability' of actions a and b (i.e. tests whether or not their range is beyond a veto threshold for the i th criterion scale). Using a set of criterion weights, it is then possible to aggregate concordance and discordance tables into an overall credibility matrix where one action can outrank the other, based on the relative positive global weight. The concordance index between actions a and b is the weighted measure of the number of criteria for which action a is preferred to action b and is given as:

$$c(a, b) = \frac{\text{Sum of weights for criteria where } a \geq b}{\text{Sum of weights for all criteria}} \tag{15}$$

$$= \frac{\sum w(k)}{\sum_{k \in A(a,b)} w(k)}, \tag{16}$$

where $w(k)$ is the weight assigned to criterion k and $A(a, b) = \{k | i \text{ is preferred to or equivalent to } b\}$. Because the concordance index value is in the interval $[0, 1]$, it can be considered as a percentage. An interval scale is used to compare the discomfort caused between the 'worst' and 'best' of each criterion. Each criterion can be assigned a different range. Given this information, the discordance index is defined as:

$$d(a, b) = \frac{\text{Maximum interval where } b \geq a}{\text{Largest range of scale}} \tag{17}$$

$$= \max_k \frac{[Z(b, k) - Z(a, k)]}{k^*} \tag{18}$$

where $Z(b, k)$ is the evaluation of alternative b with respect to criterion k and k^* is the largest range among the K criterion vectors. The value of the discordance index also falls in the interval $[0, 1]$.

PROMETHEE methods

The family of PROMETHEE methods has been designed to help a decision-maker rank partially (PROMETHEE I) or completely (PROMETHEE II) a finite set of A of n possible alternatives which are evaluated on k criteria. The basic PROMETHEE method consists of three steps: (i) defining a preference function for each criterion, (ii) defining a multi-criteria preference index and preference flows (normed flows) and (iii) complete or partial ranking of alternatives based on the defined preference structure. Following Abu-Taleb and Mareschal (1995), the basic steps of the method can be expressed as follows.

A generalised criterion is developed to correspond to each of the k criteria in order to express the decision-maker's preference structure and to withdraw scaling effects. Accordingly, a preference function $P(x, y)$ may be defined which measures the decision-maker's preference intensity for alternative a over alternative b for each criterion j . The function $P_j(a, b)$ lies in the interval $[0, 1]$. This function can be represented on a scale as shown below, where x, y represent $f_i(a)$ and $f_i(b)$, respectively.

$$\begin{aligned} P_j(a, b) &= 0 \text{ for indifference : } f_i(a) = f_i(b), & (19) \\ P_j(a, b) &= 0 \text{ for weak preference : } f_i(a) > f_i(b), \\ P_j(a, b) &= 1 \text{ for strong preference : } f_i(a) \gg f_i(b), \\ P_j(a, b) &= 1 \text{ for strict preference : } f_i(a) \gg\gg f_i(b). \end{aligned}$$

Preference of alternative a over alternative b regarding criterion j denoted here as $P_j(a, b)$ is a function of the 'distance' between their values:

$$d_j = f_j(a) - f_j(b) \quad (20)$$

A preference function index is defined as:

$$\pi(a, b) = \sum_{j=1}^k w_j P_j(a, b) \quad (21)$$

where w_j ($j = 1, \dots, k$) are normed weights associated with the criteria, so that $\pi(a, b)$ also varies from 0 to 1. Then the following preference flows can be defined. The leaving flow:

$$\varphi^+(a) = \sum_{b \in A} \pi(a, b). \quad (22)$$

The entering flow,

$$\varphi^-(a) = \sum_{b \in A} \pi(b, a). \quad (23)$$

The net flow,

$$\varphi(a) = \varphi^+(a) - \varphi^-(a). \quad (24)$$

The larger $\varphi(a)$, the better the action a is. This flow provides a complete ranking of the alternatives.

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